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# An Assessment of Pilot Control Interfaces for Unmanned Aircraft

Kevin W. Williams  
Civil Aerospace Medical Institute  
Federal Aviation Administration  
Oklahoma City, OK 73125

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## EXECUTIVE SUMMARY

The four questions addressed by this research were:

### **What kinds of control architectures are being used in current systems?**

For horizontal and vertical control of the aircraft, four levels of control were identified. The lowest level imposes direct control of the aircraft surfaces through the use of a joystick. The highest level imposes control of the aircraft through the use of programmed waypoints that determine the location and altitude of the aircraft at a given point in time. Waypoint programming is accomplished through a “point and click” computer interface. Two intermediate levels of control allow the command of either bank angle/turn rate or heading (for horizontal control) and vertical speed or altitude (for vertical control). Intermediate levels of control use physical controls for some systems like a joystick or knob, or a computer interface that either requires a pull-down menu selection or interaction with a virtual control using a computer pointing device like a mouse or trackball. All of the systems inventoried allowed waypoint control of the aircraft. Those systems that allowed direct control of aircraft surfaces only used this control level during takeoffs and landings. En route portions of flights were handled using a higher (more automated) level of control. There is a trend in the industry to replace manual control of aircraft during takeoff and landing with automation.

### **What is a common control architecture for controlling UA through visual line-of-sight?**

Direct line-of-sight control is most commonly accomplished using an interface similar or identical to a radio-controlled hobbyist control box. Some systems (e.g., Aerostar) have a modified control box that commands bank and vertical speed rather than controlling the aircraft surfaces directly. Only 3 of the 15 systems inventoried use direct line-of-sight control. Other systems, such as the Bell Eagle Eye, have a control box available for testing the movement of aircraft surfaces, but it is not used during normal flight.

### **How do different control systems (i.e., stick, menu, knobs, etc.) affect the pilot regarding basic flight and navigation parameters?**

The analysis of control levels that was accomplished in this research suggests that the manner in which flight commands are entered is not as important as the level of the command that is entered. Lower levels of control provide more immediate access to aircraft attitude but require more integration by the pilot to achieve a particular flight goal. Higher levels of control require less integration but do not allow immediate access to lower-level control needs. For example, a control system that allows direct input of vertical speed means various values of vertical speed can be achieved but requires the pilot to monitor changes in altitude to establish a particular altitude goal. In other words, the pilot has to fly the aircraft to an altitude using changes in vertical speed. On the other hand, a control system that allows direct input of altitude does not require the pilot to fly the aircraft to that altitude but also does not allow a range of vertical speeds to be input. Higher levels of control make flying the aircraft easier but restrict the flight options available.

### **Is there a lowest level of flight control that can be mandated for certain systems? In other words, what level of automation should be required for UA systems?**

Previous research indicates that the performance-level control joystick, which commands bank angle and vertical speed, is more effective than the direct control of aircraft surfaces. There is no need to allow control inputs below this level of control because there is no need to perform aerobatic maneuvers with these aircraft. In addition, benefits accrue to the pilot due to not requiring the integration of lower levels of inputs (see the report for more details). Whether control at this level is accomplished using a joystick or some other method is not relevant. The question of whether higher levels of control should be allowed as a minimum depends on the type of flight activities anticipated for the system. Perhaps as important as the level of automation is the question of how many modes a system should contain. Because mode confusion has been shown to be problematic with many automated systems (Sarter & Woods, 1997), a modeless control architecture is recommended.



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# AN ASSESSMENT OF PILOT CONTROL INTERFACES FOR UNMANNED AIRCRAFT

## INTRODUCTION

The phenomenal growth of the unmanned aircraft (UA) industry has not been without a certain number of growing pains. One outcome of the rapid growth rate has been the creation of a dazzling variety of pilot control interfaces to allow a pilot outside of the aircraft to control the flight of the aircraft from a distance. Because of the similarity to radio-controlled aircraft, many unmanned aircraft systems (UAS) make use of a joystick to control the flight. However, any casual survey of systems reveals a number of other methods for control, including knobs, buttons, menus, and various mouse-driven interfaces. Figure 1 shows the control station for the Shadow UAS.

As the UA industry continues to expand, it is inevitable that these aircraft will eventually become part of the National Airspace System (NAS). As this occurs, it is important that the Federal Aviation Administration (FAA) has standards and guidelines in place that will protect the safety and efficiency of those involved in flying in the NAS, as well as protecting the non-flying public. To develop these standards and guidelines, it is important that we understand the methods of controlling unmanned aircraft that are currently in existence and how those

methods might impact or be impacted by conventional flight operations within the NAS.

To assist in this effort, this research study was designed to assess the state of pilot control interfaces for unmanned aircraft being flown in the United States. An inventory of control architectures was completed that encompassed a wide range of UAS. A taxonomy was created to characterize these various control architectures based on the different levels of control of the aircraft that were found among the systems. The first portion of this paper describes the development of the inventory and the control-level taxonomy. The next portion of the paper presents the results of the inventory. The final portion of the paper discusses research questions that arise from the review of control architectures and suggests possible future avenues of research.

### Completing the Inventory

One difficulty in accomplishing an inventory of control architectures for UAS is that many of the manufacturers of these systems are averse to revealing very much about their interfaces to the general public. Simply calling up a manufacturer on the phone or contacting one via email and asking for a description of the pilot interface



**Figure 1.** Control station for the Shadow UAS.

**Table 1.** Manufacturers and systems included in the inventory.

Manufacturer	System
AAI	Shadow
Aerovironment Inc.	Helios, Pathfinder, Puma, Raven
Aurora Flight Sciences Corporation	Perseus, Golden Eye
Bell Helicopter Textron	Eagle Eye
General Atomics Inc.	Altair, Predator A, Predator B
Israeli Aeronautics	Aerostar
Israeli Aircraft Industries	Hunter
Northrup Grumman	Global Hawk
Pioneer UAV Inc.	Pioneer

would not work. Although prior operational experience provided information for some of the systems, visiting the manufacturers personally and speaking with them face to face was required to obtain most of the information included in the inventory.

The inventory includes 15 systems from nine manufacturers. These manufacturers and their systems are listed in Table 1.

The systems represent a wide variety of weight and performance characteristics for UA. While most were developed specifically for military use, a few, such as Aerovironment's Helios and Pathfinder, were developed with civilian applications in mind.

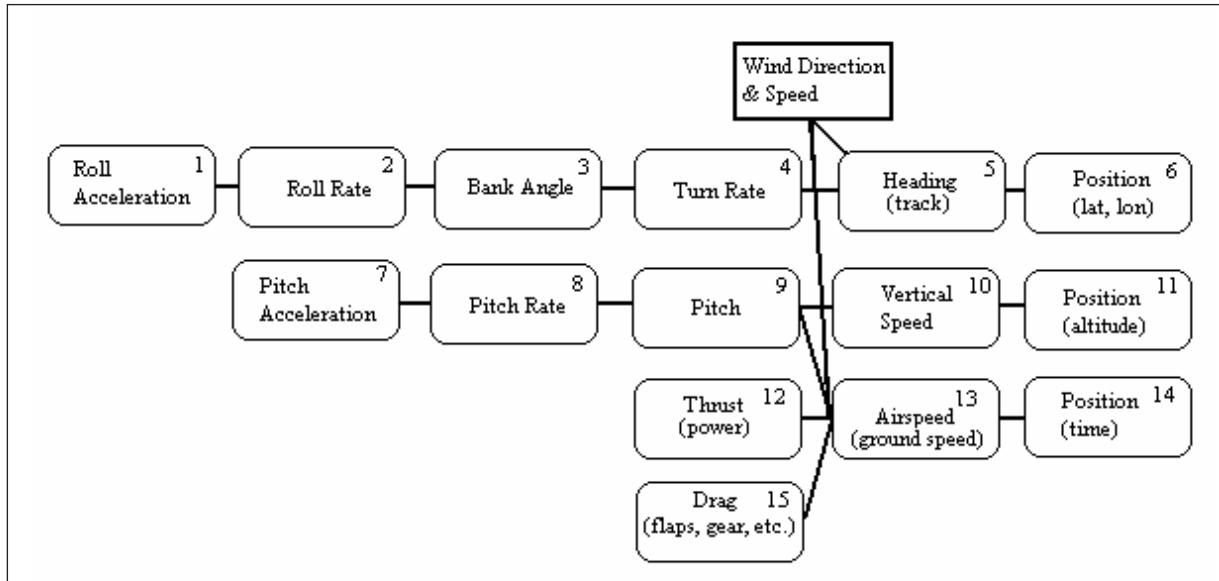
### Levels of Control

Any useful discussion of aircraft control must include the concept of levels of control. The ultimate goal of aircraft control is to cause the aircraft to reach a specific location at a particular point in time. Aircraft position is four-dimensional and can be described in terms of latitude, longitude, altitude, and time. The term "level of control" refers to the fact that the attainment of a particular position is not (usually) specified directly by the pilot but indirectly through the manipulation of lower levels of control. So, for example, to attain a particular latitude and longitude, one option is to place a waypoint on a moving-map display that corresponds to that latitude and longitude. This is the highest level of control for the pilot. Alternatively, the pilot could manipulate the aircraft heading to achieve a particular latitude and longitude. Heading manipulation is the next lower level of control from direct manipulation of latitude and longitude (through waypoints). To attain a particular heading, the pilot must control the turn rate. To attain a particular turn rate, the pilot must command bank angle. To achieve a certain bank angle the pilot must manipulate the roll rate. Finally, to achieve a specific roll rate, the pilot must control the roll acceleration. In traditional aircraft configurations, roll acceleration is manipulated directly by positioning the ailerons through movement

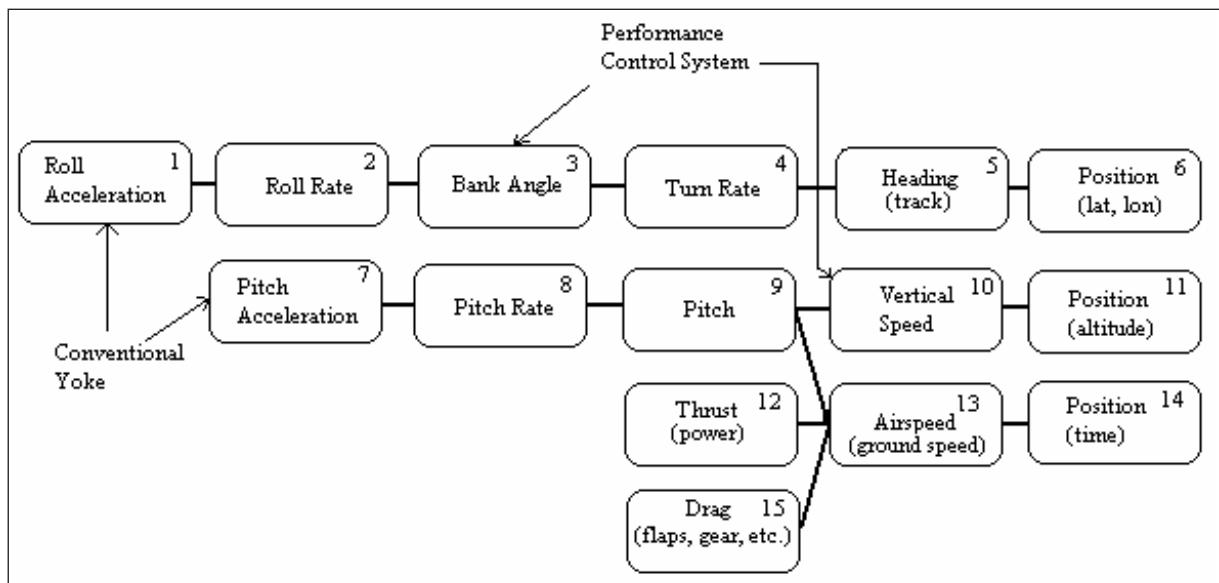
of the yoke. From the final goal state of position, described by latitude and longitude, there can be as many as five lower levels (or "orders") of control that must be integrated to achieve this goal state. Figure 2 illustrates these levels of control.

The boxes in Figure 2 are organized from left to right, with lowest order control levels on the left and highest on the right. Boxes 5 and 13 are unique in that they have an extra input in the form of wind direction and speed. Adding wind direction and speed to heading information gives you track information. Adding wind direction and speed to airspeed gives you ground speed. Some control systems control heading only, while others account for wind direction and speed and therefore control the track of the aircraft. Some control systems have inputs for airspeed, but this can be altered to account for wind speed and direction to give you ground speed. As can be seen from the figure, by looking at the top row of boxes, there are six levels where control can be initiated to achieve aircraft horizontal position, as described by latitude and longitude (boxes 1-6). Most general aviation aircraft are designed to initiate control at the lowest level (box 1, roll acceleration) through the use of a yoke. Likewise, aircraft vertical position, as described by altitude (box 11) can be initiated at one of five levels (boxes 7-11). Again, most general aviation aircraft use a yoke to initiate control at the lowest level (box 7, pitch acceleration).

Implied in Figure 2 and in the previous discussion is the notion that the most basic level of control does not have to be available to the pilot (boxes 1 and 7) and that initiating control at higher levels relieves the pilot from performing those integrations that occur at lower levels. This is achieved by automating the lower levels of control. The essential human factors task, as described by Kraus and Roscoe (1972), is determining the point at which the pilot should interface with the controls so as to minimize the difficulty of the control task without losing the minimum essential control authority to counter any reasonably likely flight contingency.



**Figure 2.** Level of control options for a fixed-wing aircraft. Please note that Figure 2 has been simplified in several ways. Many interactions between the variables have not been specified. For example, vertical speed (box 10) is influenced by lift forces, which are effected by bank angle (box 3). Airspeed (box 13) has an effect on both vertical speed and turn rate (box 4). Not all of the interactions are necessary for the pertinent discussion of level of control and so have remained unspecified in the figure.



**Figure 3.** The Performance Control System (PCS) vs. the conventional aircraft yoke.

One of the earliest attempts to reduce the number of levels of aircraft control was through the use of what was called the Performance Control System (PCS; Bergman, 1976; Fogel, Gill, Mout, Hulett, & Englund, 1973; Kraus & Roscoe, 1972). The PCS, instead of controlling roll and pitch acceleration, controls bank angle and vertical speed (see Figure 3).

With the PCS, the position of the stick left or right determines the commanded bank angle of the aircraft. Because roll acceleration and roll rate cannot be controlled directly, it is not possible to exceed a certain degree of

bank, determined by the system automation. Likewise, the position of the stick forward and backward determines the commanded vertical speed of the aircraft. Pitch acceleration, pitch rate, and pitch are determined by automation. The benefits of a PCS over a conventional yoke have been demonstrated for both manned aircraft (Bergman, 1976; Kraus & Roscoe, 1972) and unmanned aircraft (Fogel et al., 1973). These benefits included greater precision in maneuvering, fewer procedural blunders, and an increased level of residual pilot attention.

Another consequence of the PCS level of control (and for all higher control levels) is that it provides *automatic envelope protection* for the aircraft, meaning that the aircraft is prevented, through automation, from exceeding its flight-performance limitations. There is disagreement over how automatic envelope protection should be implemented, as reflected in divergent decisions by Boeing and Airbus regarding the incorporation of envelope protection in their aircraft (Chidester, 1999).

Early research on control systems by Birmingham and Taylor (1954) led to the conclusion that the fewer levels of control involved in attaining a goal state, the better. Applying this conclusion to flight control suggests that the closer you are to direct manipulation of aircraft position (boxes 6, 11, and 14), the more effective is the control architecture.

What we have shown in this analysis is that, for horizontal control of an aircraft, it is possible to interact with the aircraft at any one of six levels of control. Vertical control can be accomplished at one of five levels. Timing can be accomplished at one of three levels. When the interactions occur at a higher level, automation is required to handle all of the necessary control inputs for the lower levels. The most efficient level of control for the pilot is the direct manipulation of position and time. In UAS, this is accomplished through the use of programmed waypoints. The question that needs to be answered for these systems is whether lower levels of control are needed to execute possible flight contingencies.

This question is similar to the issue of the use of Flight Management Systems (FMS) on manned aircraft (Chidester, 1999). For example, Chidester reported a study of two aircraft cockpits (DC-9 and MD-88) that varied in regard to the level of control that was available to the pilots (Wiener, Chidester, Kanki, Palmer, Curry, & Gregorich, 1991). In the study, pilots were required to make changes to their original flight plan that involved intercepting a radial, climbing to a new altitude, and proceeding to a holding pattern location. Wiener et al. found that crews on both aircraft types completed the scenarios safely. However, there were several important differences:

- The crews of the more automated MD-88 aircraft reported significantly higher workload;
- The MD-88 crews took longer to complete the scenario;
- The MD-88 crews communicated twice as much during the abnormal period as the DC-9 crews; and
- The dominant pattern of communication was different between the crews, with the DC-9 crews having a captain's command or instruction followed by a reply from the first officer, while the MD-88 crews had a captain's question followed by a first officer response.

The authors suggested that the findings indicated a higher level of workload and uncertainty in the crews of the more automated aircraft. While the DC-9 crews easily transitioned to a lower level of flight control (called "hand-flying" by the authors), the MD-88 crews had more options regarding the level of control to adopt in accomplishing the flight changes. They could accomplish the changes by using higher levels of control, but the interface interactions were more complex and sometimes led to errors. The ramifications of these findings are relevant to the current analysis.

### Control Architecture Inventory

Based on the analysis of control levels, a taxonomy of control levels was developed for categorizing any UAS control architecture (Table 2). The taxonomy contains three types of control: horizontal movement, vertical movement, and speed. For each of these control types, the pilot can interact with the system at various levels of control, as was discussed above.

Horizontal movement of the aircraft can occur at one of four control levels in the taxonomy: 1) roll acceleration through direct manipulation of the ailerons; 2) bank angle/turn rate; 3) heading; and 4) waypoint positioning. In the table of architectures (Table 2), these levels are abbreviated R, B, H, and W, respectively. Note that some levels of control from the original analysis have been left out of the taxonomy because there are no architectures that employ these levels. In addition, the levels of bank angle and turn rate have been combined because they are very similar in nature and it was not possible, for some architectures, to collect enough information to distinguish which level of control was actually being employed.

Vertical movement of the UA can also occur at one of four control levels. These levels are: 1) pitch acceleration through direct manipulation of the aircraft surfaces; 2) vertical speed; 3) altitude; and 4) waypoint altitude. These levels have been abbreviated as P, V, A, and W, respectively, in Table 2. As with horizontal movement, some possible levels of control were not included. In addition, since altitude can be entered in conjunction with waypoint position or independently, these options were treated as two separate control levels.

Aircraft speed can be manipulated at three levels of control: 1) thrust; 2) airspeed/groundspeed; and 3) waypoint time/airspeed. These levels are abbreviated as T, A, W, respectively in Table 2.

One final column included in the table describes the pilot viewpoint for the UAS. Some systems, such as the Predator, present a viewpoint to the pilot as though inside of the aircraft looking out. This viewpoint is called an egocentric viewpoint. Other systems present a viewpoint to the pilot as though looking at the aircraft from the

**Table 2.** Control architecture inventory.

System	Horizontal Control				Vertical Control				Speed			View-Point
	R	B	H	W	P	V	A	W	T	A	W	
Aerostar		R	V	V		R	V	V	R	V	V	X
Altair		J		V		J		V	P	J <sup>1</sup>	V	G
Eagle Eye		V		V		V		V		V	V	X
Global Hawk		V	V	V		V	V	V		V	V	X
Golden Eye		V		V		V		V		V	V	X
Helios		P		V		P		V	P		V	G
Hunter	R		P	V	R		P	V	R	P	V	X
Pathfinder		P		V		P		V	P		V	G
Perseus		J		V		J		V	P		V	G
Pioneer	R		P	V	R		P	V	R		V	X
Predator A		J		V		J		V	P	J <sup>1</sup>	V	G
Predator B		J		V		J	M <sup>2</sup>	V	P	J <sup>1</sup>	V	G
Puma				V				V			V	X
Raven		J		V		J		V			V	X
Shadow			V	V			V	V		V	V	X

**Key:** **Horizontal Control** – R = roll acceleration; B = bank angle/turn rate; H = heading; W = waypoint;

**Vertical Control** – P = pitch acceleration; V = vertical speed; A = altitude; W = waypoint; **Speed** – T = thrust; A = airspeed; W = waypoint; **Viewpoint** – X = exocentric viewpoint; G = egocentric viewpoint;

**Control Inputs** – R = radio control box; J = joystick; P = physical controls; M = menu selection; V = virtual controls.

<sup>1</sup>Joystick commands airspeed if airspeed hold mode is on. <sup>2</sup>If altitude to power mode is on then altitude (and maximum rate of climb) can be commanded through a menu.

outside. This viewpoint is called an exocentric viewpoint. Typical exocentric viewpoints include depicting the aircraft on a (north-up) moving map display or flying the aircraft using direct line-of-sight from the ground. Some systems have both egocentric and exocentric viewpoints available to the pilot, so the egocentric/exocentric viewpoint might be thought of as a continuous variable. The viewpoint column in the architecture table indicates whether primary flight control is mainly accomplished using an egocentric (G) or exocentric (X) viewpoint.

In addition to indicating which level of control is used for a particular UAS, it is also important to note how the control commands are entered to the system. The actual means of commanding specific aircraft movements is unconstrained in terms of size, weight, or technology, relative to manned aircraft cockpits. However, the development of primary controls has been influenced by a few activities that have limited the types of interfaces that have been created. First, radio-controlled aircraft controls have influenced the development of new architectures. Several systems still use this type of interface, which usually consists of one or two

joysticks on a handheld box. Second, computer interfaces are used in many systems as a natural extension of the manner in which they are developed. In many systems, the flight controls are depictions on a computer screen that are manipulated through the use of a pointer – usually a mouse. In the table of system control architectures, the entries are coded as to the type of control interface that is used for a particular control level. The following codes were used: R denotes the use of radio controlled aircraft controls; P indicates the use of actual physical controls (other than a joystick) such as knobs, buttons, and switches; J denotes the use of a joystick; M indicates the use of a computer menu interface; and V denotes a virtual interface that is manipulated through the use of a computer pointing device.

Table 2 presents an inventory of the control architectures for 15 different UAS. Each UAS is described in terms of the level of horizontal, vertical, and speed (or time) control employed and the type of pilot viewpoint (egocentric or exocentric) established for the system. In addition, the type of interface used to enter control commands to the system is coded in the table.

## SUMMARY OF RESULTS

### Exocentric vs. Egocentric Viewpoint

The full set of ramifications of removing the pilot from the aircraft is unknown. However, when the pilot is removed from the aircraft, the control station can either be designed to make the pilot feel as though the operational perspective is within the aircraft looking outside (egocentric) or outside the aircraft watching it from afar (exocentric). The Predator UA is an example of an egocentric control station. The Predator UA is flown by reference to a forward “out-the-window” camera view. The Shadow UA is an example of an exocentric control station. This UA is flown by reference to a north-up moving-map display. There is no “out-the-window” view for the pilot. Whether the difference between an egocentric and exocentric design has an effect on pilot decision-making, flight performance, or awareness of flight and system parameters, has not been explored.

The majority of systems inventoried use an exocentric pilot viewpoint for en route navigation. Nine of the systems use an exocentric viewpoint exclusively. In addition, several systems that use an egocentric viewpoint (e.g., Helios) only do so for landing and takeoff of the aircraft. Most of the flight is accomplished using the moving-map display and other flight instruments in an exocentric fashion. The current trend for UA is to automate takeoffs and landings. This trend means that egocentric viewpoints are being eliminated from most systems.

One effect that the use of an exocentric viewpoint has had is on the design of displays. In addition to the use of moving-map displays for every system, other displays have also been designed with an exocentric viewpoint. An example is the attitude indicator for the Global Hawk UAS (see Figure 4).

Unlike traditional attitude indicators, the attitude indicator for the Global Hawk is known as an “outside-in” display. In a traditional attitude indicator, the aircraft symbol stays stationary in the center of the display, and the horizon line on the display moves in relation to the aircraft symbol. This type of indicator is called an “inside-out” display because the horizon line moves as though it were being viewed from inside of the aircraft looking out. With an outside-in attitude indicator, the horizon line remains stationary and the aircraft symbol moves. Whether an outside-in attitude indicator is more suited for use with unmanned aircraft has not been demonstrated empirically, although the majority of studies have found this type of display superior to the traditional inside-out display for preventing roll-reversal errors and for recovering from unusual attitudes (Previc & Ercoline, 1999).

### Levels of Control

As can be seen from Table 2, only two of the 15 systems inventoried (Hunter and Pioneer) allow direct control of flight surfaces. These systems only allow this level of control for their external pilots through the use of radio-control boxes, similar to what hobbyists use (Figure 5). On the other hand, every system had a form of waypoint programming available. However, the interface for setting or editing waypoints was not always a part of the pilot interface. For example, the interface for programming waypoints for the Puma and Raven UAS required a separate laptop. The primary pilot control interface for these systems is a handheld box with a limited set of physical controls for making menu selections (Figure 6).

The external pilots for the Hunter and Pioneer UAS control the aircraft only during landings and takeoffs, and they maintain awareness of aircraft position and attitude through direct visual line-of-sight with the aircraft. There are plans for both the Hunter and Pioneer to replace the external pilot with an automated takeoff and landing system.

Most of the systems inventoried have multiple levels (or modes) of control available to the pilot. Usually, the control level is selectable through a switch or knob on the control panel, although some systems use a graphical or menu interface for selection of control level. Differences between these various methods of selecting the control level are probably irrelevant, as long as the pilot has a clear indication of the control level available.

One problem with the use of multiple levels of control is workload and/or distraction associated with the selection of which control level to use (Chidester, 1999). A second problem is the possible confusion of the pilot as to the currently selected level of control. This problem of “mode awareness” has been documented for highly automated manned aircraft cockpits (Sarter & Woods, 1997). The interface for the Predator A and B has several control modes available that alter the manner in which control inputs affect the system (see Figure 7).

The control interface for the Predator models employs a joystick (center left, Figure 7) for normal horizontal and vertical control inputs (unless the aircraft is flying programmed waypoints or certain autopilot modes). The Predator uses a Stability Augmentation System (SAS) that is essentially the same as the performance control system level of automation discussed earlier. Side motion of the joystick commands bank angle. Longitudinal motion of the joystick commands rate of climb under normal configuration of the SAS. However, if the airspeed hold mode is on, longitudinal motion of the joystick commands airspeed. This is similar to the command of airspeed for



Figure 4. Global Hawk flight display.

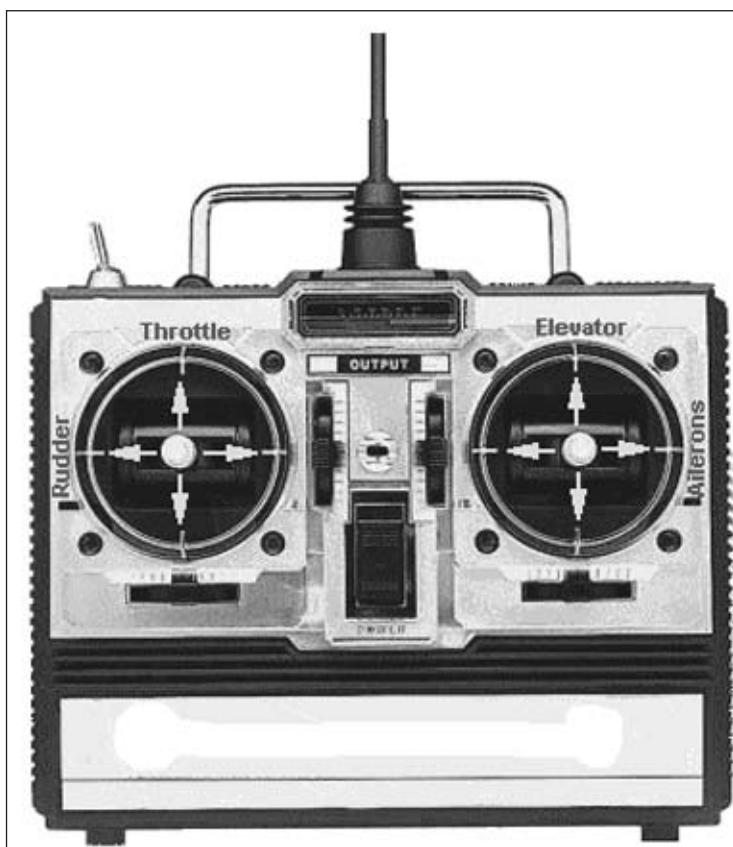


Figure 5. Controller for radio-controlled aircraft.



Figure 6. Control box for Raven and Puma UAS.



**Figure 7.** Control station for the Predator UAS.

the Hunter UAS. In both cases, airspeed changes are accomplished through changes in pitch and power of the aircraft rather than only through changes in power.

The problem here, at least for the Predator, is that the same control is used in the same manner to command two different inputs, climb rate and airspeed. The pilot has to be fully aware of which mode is active to understand what is being commanded when the joystick is moved forward or backward. In addition, since airspeed changes are accomplished through changes in pitch, the pilot might get a false sense that climb rate has been commanded instead of airspeed because of changes in the attitude indicator.

### Control Devices

Actual physical controls (i.e., joystick, knobs, switches, etc.) were employed in eight of the 15 systems that were inventoried. Figure 8 shows an example of an interface that employs physical controls. This interface is for control of the Perseus UAS. The use of small joystick controls, such as those used in the Perseus interface, has been criticized as suboptimal for efficient control of an aircraft (Gawron, 1998). However, the effect that such controls have on flight performance of these systems has not been tested empirically.

For those systems that did not use physical controls, the primary means of controlling the aircraft was the use of a computer screen that displayed a virtual control/display combination that could be manipulated through the use of a computer pointing device, such as a trackball or mouse. Other systems allowed for inputs in the form of menu selections using either a pointing device or through the use of function keys on a standard keyboard.

Shown in Figure 9 is an example of a virtual control/display combination. This control is used for commanding the bank angle/turn rate of an aircraft. The pilot would turn the aircraft by clicking and dragging the diamond

to the left or right along the rectangle located below the heading indicator. The direction that the diamond is dragged commands the direction of the turn of the aircraft. The distance from the center of the rectangle determines the rate of turn or angle of bank commanded. The heading indicator shows both an indication of the current heading and the commanded heading.

In addition to this example, other types of virtual controls include pushbuttons for selecting turns, sliders for commanding engine speed, and up/down arrow buttons for commanding changes in heading or altitude.

## DISCUSSION

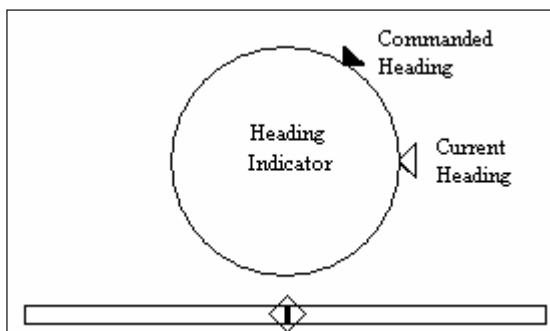
Current UA employ a wide variety of control architectures. While there are still a few systems that use direct control of aircraft surfaces, this level of control is used only by external (i.e., direct line-of-sight) pilots during landing and takeoff. Most of the systems inventoried employ some level of automation at all available levels of control, and all of the systems have a waypoint level of control that allows the aircraft to fly at least a portion of the flight without pilot intervention.

The viewpoint of the pilot for a majority of the systems is exocentric. There is no research to suggest that an exocentric viewpoint has any negative effect on the pilot in terms of decision-making, piloting skills, or awareness of flight parameters. However, it has been suggested that there might be negative consequences from the pilot not having a shared fate with the aircraft (McCarley & Wickens, 2005). Whether an exocentric viewpoint diminishes the feeling of shared fate or not is unknown.

Attitude information is sometimes given in the form of an outside-in display and sometimes as an inside-out display. The outside-in display has been shown to be more effective for recovery from unusual attitudes (Previc & Ercoline, 1999), but the level of automation employed



**Figure 8.** Control interface for the Perseus UAS.



**Figure 9.** Example of a virtual control for bank angle/turn rate.

for UAS should prevent the onset of unusual attitudes from ever occurring. There is no empirical support in regard to which format is the most effective for the types of piloting activities expected for UAS.

### **Direct Line-of-Sight Control**

Two of the systems inventoried (Pioneer and Hunter) employed direct line-of-sight control for landings and takeoffs. This control level involved the direct manipulation of aircraft surfaces, which was the least automated control level. Although the trend seems to be that these systems are being upgraded with automated takeoff and landing features, it is still possible that commercial systems wishing to fly in the National Airspace System might use direct line-of-sight control during takeoff and landing. The available accident data for these types of systems has indicated a relatively high number of landing accidents (Williams, 2004). It has been suggested that the primary reason for many of these accidents is the inconsistent mapping of the controls to the movement of the aircraft (McCarley & Wickens, 2005; Williams, 2004). However, a separate study conducted by the U.S. Air Force did not find a high number of landing accidents for these systems (Thompson, Tvaryanas, & Constable, 2005).

One difference between the two data sets is that the data showing more landing accidents included training accidents (Williams, 2004), while the data showing fewer landing accidents involved more operational accidents (Thompson et al., 2005). While there might be several factors involved, one possibility for the difference in the number of landing accidents is that the operational data involved pilots with more flight experience than those represented in the training data. This suggests that pilots might be able to overcome the problem of inconsistent mapping with sufficient training on the systems. However, research is required to determine the effectiveness of training on overcoming the problem of inconsistent mapping before decisions are made regarding the use of these UAS within the National Airspace System. It might also be important to assess the effect of other factors, such as fatigue or stress, on pilots performing with these types of systems.

### **Handling Flight Contingencies**

All of the systems inventoried can be controlled through the use of waypoints on a moving-map display. This makes sense, given that the specification of waypoints represents the highest level of control; one that does not require the pilot to integrate lower control levels to achieve a desired flight goal. In this sense, waypoint control is the easiest method of control for the pilot.

Waypoint control is easy, but is it adequate for all possible flight contingencies? Flights within the NAS must sometimes respond to directives from Air Traffic Control to change heading, change or hold an altitude, or proceed to a different intersection. In addition, a change in the flight path might be required in response to the presence of traffic or weather that needs to be avoided.

While it is possible that these contingencies could be handled through the manipulation of waypoints, the speed and efficiency of the response might be compromised. For this reason, it is expected that lower levels of flight control will be needed. An analysis is required of expected flight activities to anticipate the range of flight contingencies, away from a preprogrammed series of waypoints, that might be encountered during flights within the NAS.

If, for example, the turn rate or vertical speed were found to be critical for certain flight contingencies, then waypoint control would not be adequate. The system would require a lower level of control. However, there is no reason that a level of control lower than the performance control system levels is required for UAS (unless there is a requirement for aerobatic capability for an aircraft). Work on the task of identifying flight contingencies has been initiated within the standards-making organizations, SAE-G10 and RTCA Special Committee 203.

### **Levels of Autonomy of Unmanned Aircraft**

Instead of providing lower levels of pilot control to manage flight contingencies outside of a set of preprogrammed waypoints, a second possibility is to provide the UAS with the ability to establish its own flight goals outside of those provided by the pilot; in other words, to provide the UAS with a certain degree of autonomy. At this time, even the most automated unmanned aircraft (e.g., Global Hawk) have no autonomy. These aircraft can only follow a route that has been entered by a human, or deviate from the route through human control. Autonomy refers to the ability of the aircraft to formulate its own flight goals, independent of the human (Clough, 2000). Using the analysis provided in this paper, there are several levels of autonomy that can be possessed by a UA. These levels are based on the waypoint level of aircraft control.

For the first level of autonomy, the aircraft does not generate its own waypoints but can initiate a deviation from the waypoint pathway through a change in heading, altitude, or speed. The most basic type of deviation in this regard would be to initiate an orbiting pattern (or hover maneuver for rotary aircraft). These deviations could be in response to a perceived threat on the part of the aircraft such as other air traffic or severe weather. For

this first level of autonomy, no new waypoints are created and once the threat has been resolved, the aircraft returns to the pathway and resumes operations.

At the second level of autonomy, the aircraft creates a new set of waypoints to accomplish a specific task. The task could be a response to a threat, as before, with the addition that the flight deviation requires more intricate maneuvering than allowed through a simple change in heading or altitude.

The third level of autonomy is a pathway deviation. In this case, the original flight path is abandoned and a new pathway is generated, ending at an unplanned alternate. The degree of software sophistication at this level of autonomy is quite complex and probably will not be available in the near future.

The fourth level of autonomy is the creation of a pathway based on a higher-level goal (e.g., a fire-fighting aircraft that is fed the coordinates of a fire and allowed to plan and autonomously execute the flight). Again, the software sophistication for this level of autonomy is not available yet.

### Future Efforts

The specification of the required level of control for a particular UAS requires a full understanding of all the flight contingencies for the type of operations that can be accomplished (or allowed) with the aircraft. In addition, it is important that we develop an understanding of how interactions at various levels of control affect pilot performance in terms of precision of flight, awareness of flight parameters, and decision-making. There might also be an interaction with levels of control of the general type of input device employed (e.g., a physical control such as a knob vs. a virtual control manipulated with a mouse).

If multiple levels of control are available to the pilot, there is a potential problem of mode confusions, as have been observed with manned aircraft (Sarter & Woods, 1997). One way to avoid this problem is to create an interface that does not require separate modes to access the various levels of control. Such a "modeless" interface would require clearly defined procedures for accessing all of the required control levels without having to establish a flight mode. The most likely interface would probably use waypoint manipulation, along with other virtual controls for accessing lower-level control commands.

It is unreasonable to insist that the pilot be able to specify a range of vertical speeds or turn rates if all flight contingencies can be accommodated using a standard climb or turn rate. However, the specification of flight contingencies might require certain flight restrictions

that limit the number of contingencies needed for operation of the systems. For example, aircraft that have a restricted climb rate might not be placed in the traffic pattern with certain other types of aircraft and might be barred from certain types of airspace (e.g., class B). There is, unfortunately, no simple solution for the appropriate control architecture for these systems. The solution to this problem requires the simultaneous consideration of human factors issues, operational requirements, and rule-making efforts.

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